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Effect of cattle genotype and feeding regime on greenhouse gas emissions intensity in high producing dairy cows

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Abstract

Improving milk production through livestock feeding and genetics is a promising approach for reducing greenhouse gas emissions (GHG) from dairy production systems. This study investigated emissions intensity, defined as the global warming potential (GWP) per unit energy corrected milk (ECM) output, of high-producing dairy systems. Objectives of this study were: to determine the effect of forage regime and cattle genetic line on GHG emissions from the life cycle of four directly comparable dairy production systems; to examine differences amongst contributing GHG emissions sources, and to identify key parameters contributing the most uncertainty in overall GWP. Life cycle analysis (LCA) was conducted based on seven years data collected from a long-term Holstein-Friesian genetic and management systems project. The four dairy production systems comprised two feeding regimes of High and Low Forage applied to each of two genetic lines. The Control line

represented the average UK genetics and Select line representing the top 5% of UK genetics for milk fat and protein.

Select genetic line animals managed under Low Forage regime was estimated to hold potential to reduce emissions intensity by 24% compared to Control genetic merit cows managed under a High Forage regime. Individually, improving genetic merit of the herd and implementing Low Forage regime hold potential to reduce emissions intensity by 9% and 16% respectively. Key factors in the differences amongst systems were greater off-farm emissions under Low Forage regime, and greater on-farm nitrous oxide emissions associated with High Forage. In contrast to overall emissions, the emissions intensity was lower in Low Forage groups than in High Forage groups because of high milk yield in Low Forage groups. Six key parameters contained the greatest influence on uncertainty in results. These included: three Intergovernmental Panel on Climate Change (IPCC) coefficients concerning indirect emissions from volatilized nitrogen (EF_4), direct nitrous oxide emissions from nitrogen input to soil (EF_1), and emissions from direct deposition of excreta at pasture ($EF_{3\text{ PRP}}$); and three system-specific emissions factors for animals' excreted nitrogen rate, enteric methane and manure methane. The coefficients EF_4 , EF_1 , and $EF_{3\text{ PRP}}$ should be prioritized for better definition in order to minimize uncertainty in future studies.

Key Words: life cycle assessment, dairy, forage, genotype, greenhouse gas, emissions intensity

1. Introduction

1.1. Background

There has been increasing attention paid during the past decade to the contribution of food production to climate change and the challenge faced by society's current demand for products such as meat and dairy. Globally, the dairy sector contributes 4% of the total anthropogenic greenhouse gas (GHG) emissions (FAO, 2010). If the dairy industry is to meet the growing global demand for dairy products, ways to minimize GHG emissions per unit product will become increasingly important. Gerber et al. (2011) defined the GHG emissions per unit physical output as the emissions intensity of dairy production. Many countries have established ambitious GHG reduction targets, and the UK dairy industry has identified a target of 20-30% reduction by 2020 (Dairy Roadmap, 2013) compared to 1990 levels. The magnitude of emissions means that any potential improvements made in the global warming potential (GWP) of dairy production systems will make a substantial contribution towards attaining climate change targets around the world.

1.2. Greenhouse gas emissions from dairy production systems

Component GHG contributing to the total GWP of dairy production systems arise from processes both on and off the farm. Methane (CH_4) arises from enteric fermentation in ruminant animals, and from an aerobic fermentation of stored animal manures. Enteric CH_4 is influenced by the animal's feed intake, feed composition and the type of feed consumed (Chagunda et al., 2009; Garnsworthy et al., 2012). Emissions of nitrous oxide (N_2O) arise both directly and indirectly from multiple on farm sources (de Boer, 2003). These include the

1 deposition of manure and urine on pasture, application of manure and chemical fertilizers to
2 crops, and from decomposition of crop residues in the soil (IPCC, 2007). Carbon dioxide
3 (CO₂) emissions derive mainly from energy use on the farm and in the processes surrounding
4 external production and transport of purchased feeds and fertilizers. The dynamic relationship
5 between the operational and natural processes of a dairy production system leads these three
6 GHG to be inexorably linked. Thus even a small shift in the balance of these GHG emissions
7 produced may lead to a substantial difference in overall GWP.

8
9 Steinfeld et al. (2006) stated that the most promising approach for reducing emissions from
10 livestock systems is by improving the efficiency of livestock production through feeding and
11 genetics. It has been shown that high yielding dairy cows with high feed intakes are
12 associated with a lower enteric CH₄ output per unit milk (Garnsworthy, 2004; Casey and
13 Holden, 2005; Bell et al., 2010). However, Chagunda et al. (2009) showed that although
14 increasing milk yield was associated with a reduction in enteric CH₄ per unit milk, there
15 could be an increase in excreted waste nitrogen per unit milk and per hectare of land used
16 depending on the genetic merit of animals and the specifics of the production system. It has
17 also been demonstrated that while implementing an organic system can reduce overall
18 emissions of CO₂ and N₂O, the reduction in GWP may be nullified by lower production and
19 an inherent overall increase in enteric CH₄ (de Boer, 2003). Weiske et al. (2006) also noted
20 that, due to the trade-offs amongst dairy GHG emissions, many mitigation measures
21 suggested in the literature do not always result in the expected reduction potential when
22 evaluated at the farm level. The overall GHG pollution potential from dairy production
23 systems is therefore a dynamic process which should be assessed at a whole systems level in
24 order to optimize the balance of the total output of pollutants against milk production. This

whole system analysis can be performed using a method such as Life Cycle Assessment (LCA).

Over the past decade, studies have been undertaken at system level examining the relationships between GHG in dairy farms. Many studies have been aimed towards demonstrating the application of the LCA method in dairy farming (van der Werf et al., 2009; O'Brien et al., 2011). Furthermore, LCA studies assessing a whole farm system have been conducted mainly in the context of providing a comparison between the environmental efficiency of conventional and organic systems (de Boer, 2003; Thomassen et al., 2008), or between typical systems at a national level (Cederberg and Flysjö, 2004; Saunders and Barber, 2007). A recent study by Kristensen et al (2011) observed the large variations in GHG emissions per kg product that existed amongst farms within and not between conventional and organic production systems. Studies at production system level have not examined in depth the potential that exists to reduce emissions intensity within a herd through maintaining cows of different genetic merit under different feeding and management regimes.

1.3. Objectives

Objectives of this research were: (1) to determine the effect of forage regime and cattle genetic line on GHG emissions from the life cycle of four directly comparable dairy production systems; (2) to examine differences amongst contributing GHG emissions sources, and; (3) to identify key parameters contributing the most uncertainty in overall GWP.

2. Materials and Methods

2.1. Dairy Production Systems

The study was based on Scotland's Rural College's (SRUC) established long-term Holstein-Friesian genetic and management systems project, situated at SRUC Dairy Research Centre, Crichton Royal Farm (CRF), Dumfries. Data used were collected over seven years, from January 2004 to December 2010, and incorporated specifics of four distinct dairy production systems within a conventional farm. Animals were maintained in two feeding regimes; High Forage (HF) and Low Forage (LF). The HF regime aimed to provide 75% by dry matter (DM) of the herd's total mixed ration (TMR) diet when indoors from home grown forage crops (ryegrass silage, whole-crop maize, whole-crop wheat alkalage) and the remainder of the ration composition coming from purchased concentrated feeds (including: distillers grains, rapeseed meal). In addition, HF cows were grazed ryegrass pasture when available, typically from March to November, therefore the total home grown element of the HF cows' annual diet was greater than 75%. Contrasting, the LF groups were fully housed all year round and fed a TMR comprising 45% by DM of the same home grown forages, with 55% from purchased concentrates (including: wheat, distillers grains, sugar beet pulp, soya meal) imported onto the farm (Chagunda et al., 2009). Within each forage regime, animals comprised two contrasting genetic lines. Control (C) animals were bred to be of average UK genetic merit for milk fat and protein production, and Select (S) animals represented the top 5% of UK genetic merit (Pryce et al., 1999). The Langhill genetic lines have been continuously managed as part of a long-standing dairy cow breeding study since the 1970's. The representativeness of the selection criteria was maintained in each year of the study (Hinks, 1976). Maintaining the specifics of these groups in the long term genotype x feeding regime project resulted in four divergent dairy production systems – HFC, HFS, LFC and

LFS (Chagunda et al., 2009). These systems were representative of the interaction between forage regime and genetic line (Pryce et al., 1999), and also offer a representative cross-section of existing and potential dairy production systems in the UK. Animals were managed in a 3 lactations programme before moving out of the systems study, with all-year round calving, and herd numbers maintained at approximately 50 cows in each group. The 3 lactations management was considered applicable to UK dairy systems as the average dairy cow lifespan is noted to be 3.3 lactations (FAWC, 2009). Management in 3 lactations applied a comparable replacement rate amongst systems, however differences existed in the involuntary culling rate. Cows were milked three times daily, received equal treatment regarding health and fertility and were under responsibility of the same herdsman. Select and Control cows were managed together and groups retained in the same building when housed. Young stock from all groups were managed together and fully housed. A selection of traits and characteristics describing the four dairy production systems is presented in table 1.

2.2. Data collection

The life cycle inventory treated each of the Langhill systems as a whole farm, accounting for not only the milking herd but replacement animals as well. All farm-derived data were a true representation of management at CRF, and were summarized as inputs by calendar year. Livestock populations were categorized by age as follows: cows (lactating or dry cows), pregnant heifers older than 24 months, heifers aged between 12-24 months, and between 0-12 months. The average population of each livestock age category was determined as the total number of animal feed days divided by 365. Bull calves were not included in this study. Milk yield was recorded for individual cows at every thrice daily milking. Data on milk composition (milk fat and protein) were recorded from samples collected from each cow once

a week. Live-weights were recorded daily for cows after every milking and weekly for dry cows, and replacement stock. Specific diets were fed depending on animals' production system, age, and stage of pregnancy where appropriate. The formulated TMR was offered once a day to each group and daily feed intake of individual lactating cows was recorded using automated HOKO feeding gates (Insentec BV, Marknesse, The Netherlands). Applying the estimates from Bell et al. (2010), dry matter intake (DMI) of HF cows grazing pasture was 19.2 kg day⁻¹ for Control and 20.8 kg day⁻¹ for Select cows. Herbage intake of grazing cows is difficult to predict. However, the research by Bell et al. (2010) compared several leading methods for predicting herbage intake, and made robust estimates for Langhill systems based on the cows' energy balance, selecting a method which minimized uncertainty. Dried-off cows were initially fed a specific drying-off diet, followed by a transition period ration for the three weeks prior to predicted calving date. The transition diet comprised one-third of the lactating cow TMR plus 5 kg of wheat straw. Compositions of the Langhill TMR formulations are presented in table 2. All young stock were managed together on the same diet irrespective of their system. A typical diet for young stock, from birth to the pre-calving transition period, was derived in consultation with the senior dairyman at CRF (Kelly, 2010) and the Farm Management Handbook (Craig and Logan, 2012). Samples of all forages and rations were collected weekly and analyzed for DM and metabolizable energy (ME) content, crude protein (CP) content and digestibility.

Three forage crops were grown at CRF: ryegrass silage, whole-crop wheat alkalage and whole-crop maize silage. Ryegrass silage was harvested in three cuts, typically in April, July and September. Harvest yields from all three crops were retained on farm to be used as forages for indoor feeding, with additional improved land employed as ryegrass pasture for grazing. All harvested crops were stored in covered outdoor silage clamps. Dry matter losses were considered during harvesting (categorized as mechanical, respiration, wilting and

leaching losses), ensiling (surface, effluent and invisible losses) and unloading (mechanical losses) of forages (Bastiman and Altman, 1985; MacDonald et al., 1991). Average crop yields and on-farm land use over the period are presented in table 3. A combination of animal manure and manufactured fertilizers was applied to crops, in common with conventional farming system practice. Manure was applied via slurry injection, while purchased fertilizers applied included urea, ammonium nitrate and a range of NPK fertilizers. The average annual application of purchased nitrogen over the period is presented in table 3. Animal manures were managed as either liquid storage, solid storage or deposition at pasture. Liquid system manure was contained in a reservoir underneath the main steading before pumping into storage in two uncovered outdoor slurry tanks, while solid manure was collected daily in an uncovered outdoor store. All stored slurry and manure was subsequently retained on-farm and applied to land as manure fertilizer. All manure from milking parlour, and from the continually housed LF milking cows was transferred into a liquid slurry storage system. The proportion of manure from HF cows collected in liquid storage or deposited at pasture was relative to the amount of time spent grazing. All young stock, dry and transition cows were fully housed, and their manure was managed as solid storage farm yard manure (FYM). Electricity invoices were obtained from CRF for the period, and all tractors and other farm machinery ran on red diesel. Average data covering the livestock inputs, energy use and production level of the different systems are presented in table 4.

2.3. Life Cycle Assessment

2.3.1 Goal and Scope Definition

The boundary of the current LCA was defined as from ‘cradle to farm gate’ (BSI, 2011), covering the stages from the extraction or acquisition of raw materials up to the point at which the product milk left the farm. A flow diagram displaying the on- and off-farm processes included within the LCA boundary is presented in figure 1. The study did not therefore account for the subsequent processing and transport of consumer dairy products. However, this approach was appropriate because 80% of dairy product GHG emissions are associated with the production phase (Yan et al., 2011), and the product raw milk from the four systems was treated equally in post-farm processing. The study did not take account of capital goods, such as the purchase and upkeep of buildings, machinery and of farm personnel. Inputs such as medicines, seeds, detergents and disinfectant were excluded because of their minimal impact upon the system (Cederberg, 1998). No account was made of carbon sequestration or loss resulting from land-use change in this study. The time frame of each assessment was one calendar year, removing any influence of seasonality. The functional unit in this study was ‘one kg of energy corrected milk (ECM) leaving the farm gate’. Following Sjuanja et al. (1990), the equation used in this study was:

$$\text{ECM (kg)} = 0.25M + 12.2F + 7.7P$$

where M = milk yield (kg), F = fat content (kg), P = protein content (kg).

All forage crops and manure were retained on the farm, and the value of surplus and culled livestock was defined to be the only co-product of the systems. Therefore, the International Dairy Federation (IDF) method of mass allocation between milk yield and sold stock was employed (IDF, 2010). System-specific allocation values were determined for each system in each year of the study. The average allocation value to milk was 83% (sd=4%), 88% (2), 81% (5) and 87% (4) for LFC, LFS, HFC, HFS respectively. These figures are noted to be broadly consistent with the economic value of 85% allocated to milk which has been employed by several previous studies (including: Cederberg and Mattsson, 2000; Basset-

Mens et al., 2005; Saunders and Barber, 2007) and the default value for physical allocation to milk of 85.6% recommended by the IDF (2010).

2.3.2 Inventory Analysis

System specific emissions factors were estimated for enteric methane, methane from anaerobic fermentation of manure, and animals' excreted waste nitrogen. Daily enteric CH₄ was estimated using the non-linear equation by Mills et al. (2003) based upon metabolizable energy intake (MEI). The equation used was:

$$\text{CH}_4 (\text{MJ day}^{-1}) = 45.98 - 45.98 \exp^{-0.003 \times \text{MEI}}.$$

Emissions factors for CH₄ arising from deposition and management of animal manures were calculated using equations by the IPCC (2006). Excreted nitrogen was determined as the difference between nitrogen consumed and nitrogen utilized in milk production, growth and maintenance. Nitrogen consumed was estimated from weekly averages of cows' dry matter intake (DMI) and weekly feed samples to determine crude protein (CP) content of their diet.

Emissions of N₂O arising from manure management and deposition at pasture, application of all fertilizers to the soil, and from crop residues, were estimated using IPCC (2006) equations. Emissions factors employed covered direct N₂O emissions, and indirect N₂O emissions from volatilization, leaching and run-off, and direct emissions of CO₂ arising from applied urea. Coefficients used for emissions associated with the production and delivery of manufactured fertilizers were sourced from the Carbon Trust Footprint Expert (Carbon Trust, 2010b). Emissions factors employed for the production, delivery and use of energy and fossil fuels were sourced from the Department for Environment, Food and Rural Affairs (DEFRA, 2011). The specific emissions factors employed in this study are presented in table 5.

Embedded emissions associated with the production and delivery of purchased feeds were determined using Footprint Expert (Carbon Trust, 2010a; 2010b). Allocations were made between co-products where they existed for imported concentrates, for example between rapeseed oil and rapeseed meal. These allocations were made according to the mass allocation values identified by Cederberg and Mattsson (2000), which were similarly employed by Bell et al. (2011). Allocations of embedded emissions were made as follows for purchased feed components: sugar beet (66% sugar, 22% beet pulp, 12% molasses); soya (20% oil, 80% meal, not accounting for land use change); rapeseed (40% oil, 60% meal). A breakdown of estimated land use and emissions embedded in purchased feed blends for High forage (HF) and Low forage (LF) rations is presented in table 6.

2.3.3 Impact Assessment

Environmental impact assessment was conducted using a modified version of the SAC Carbon Calculator (SAC Rural Business Unit, 2011), designed specifically for use in the Scottish agricultural sector and implementing IPCC Tier 2 methods (IPCC, 2006). Liaising closely with the developer, this study was able to implement system specific coefficients for enteric and manure CH₄ and excreted nitrogen, as well as calculator inputs including energy use, animal production and feed intake, digestibility and crude protein content. Emissions of kgCO₂e for major GHG were calculated using conversion factors for a 100 year time horizon, defined to be 25 and 298 for CH₄ and N₂O respectively (IPCC, 2007). The total GWP was estimated for each of the four Langhill systems - LFC, LFS, HFC and HFS – for each of seven full calendar years of the study period.

2.4. Statistical Analysis

The effect of forage regime and genetic line upon the impact category was assessed using analysis of variance (ANOVA) employing a general linear model (GLM) procedure. The model used was:

$$y_{ijk} = \mu + F_i + G_j + (F \times G)_{ij} + A_{ijk} + \varepsilon_{ijk},$$

where y_{ijk} is the impact category (global warming potential, land use) expressed per kg ECM; μ is the overall mean; F_i is the fixed effect of feeding regime (Low Forage or High Forage); G_j is the fixed effect of genetic line (Control or Select); $(F \times G)_{ij}$ is the effect of production system (LFC, LFS, HFC, HFS); A_{ijk} is the random effect of calendar year (2004-2010); ε_{ijk} is the random error term. Significant differences between variables were determined by conducting pairwise comparisons using the Tukey method. All statistical analysis was conducted using Minitab 16.

2.5. Sensitivity Analysis

The SAC Carbon Calculator which was employed in this study was a deterministic model, producing a single figure representing the GWP of an agricultural production system for an annual period. A stochastic simulation analysis was therefore conducted in order to assess the effect of statistical uncertainty in IPCC coefficients and system-specific emission factors. Sensitivity Analysis determined which emissions sources, and which specific coefficients within those sources, were contributing the largest uncertainty to the estimated GWP. Uncertainty in this analysis refers to an estimate of imprecision in the result due to the different variation in the inputs, as defined by Basset-Mans et al. (2009). Monte Carlo simulations were performed employing the @Risk package (Palisade Corporation, 2012a) in a similar way as has previously been employed in other dairy studies (e.g. Shalloo et al.,

2004; Basset-Mens et al., 2009; Zehetmeier et al., 2014). Mean values for farm input data for each system were estimated from the life cycle inventory covering the 7 year period of the study. Probabilistic distributions for inventory emissions factors were applied based on the uncertainty parameters specified by the source of the coefficient (IPCC, 2006; Carbon Trust, 2010b; DEFRA, 2011). In the absence of information about the shape of the parameters' distribution, a beta-pert distribution was applied, as demonstrated by Brown et al. (2001). Employing this distribution preserved any asymmetry in the parameter distribution. The estimated system-specific coefficients for CH₄ and excreted nitrogen were normally distributed. Uncertainty in the contribution of enteric CH₄, estimated using the equation of Mills et al. (2003), was defined by the range of variation in MEI. The uncertainty parameters and distributions applied to emissions factors were those presented in Table 5. Monte Carlo simulations consisting of 10,000 iterations were performed for each of the Langhill systems. The @RISK procedure employed stepwise multiple regression (Palisade Corporation, 2012b), and determined regression coefficients explaining how much of the observed uncertainty in the resulting distributions could be attributed to the uncertainty associated with each contributing emissions source. A normalized multiple regression coefficient of 0 indicated no relationship between the input and output, while a value of 1 or -1 indicated a 1 or -1 standard deviation change in the output for a 1 standard deviation change in the input. Within each contributing source, regression coefficients were also determined for the emissions factors listed in table 5, employed in the impact assessment calculations for each production system.

3. Results

3.1. Effect of forage regime and genetic line

Results from ANOVA, showing the effect of forage regime and genetic line upon the GWP of contributing sources, are presented in Table 7. All results presented take into account the allocation of emissions between product milk and meat. Results for the effect of forage regime and genetic line upon the on-farm, off-farm and total land requirement are presented in Table 8.

3.1.1 Total overall global warming potential

The most GHG efficient system was defined as having the lowest emissions intensity, i.e. lowest GWP per unit ECM. The effect of the interaction was significant and all four production systems were different ($p < 0.001$) from each other. The random effect of year was significant ($p < 0.05$) although accounted for a very low proportion of the overall variation. LFS was the most GHG efficient system (least squares mean = $0.87 \text{ kg CO}_2\text{e kg}^{-1} \text{ ECM}$, standard error of the mean = 0.016) ($p < 0.001$). The HFC system had the highest emissions intensity ($1.14 \text{ kg CO}_2\text{e kg}^{-1} \text{ ECM}$). Emissions intensity of LFS was therefore 24% lower than that of HFC. Within a forage regime Select was more efficient than Control, and Low Forage more efficient than High Forage with the same genetic line ($p < 0.001$). Emissions intensity was observed to be 16% lower in Low Forage regime and 9% lower in the Select line ($p < 0.001$). Methane contributed the highest to the overall GWP, comprising 51-52% of the total in all systems. On-farm CO_2 emissions made the lowest contribution for all systems. In the two HF groups, emissions of N_2O (23-24%) contributed more to the overall GWP than the indirect CO_2e (18%) associated with off-farm processes. Off-farm emissions include those embedded in production and delivery of purchased feed, bedding, and manufactured fertilizers. Conversely, for the two LF groups, contribution from off-farm CO_2e (21-22%)

was greater than that from N₂O (19%). Average annual ECM yield per cow was observed to be 9246, 10753, 7281 and 8189 kg in LFC, LFS, HFC and HFS respectively. Annual milk yield per cow was 48% higher in LFS than in HFC, representing a difference of over 3000 kg per cow between the systems. Milk yield per cow was therefore a key factor in this study.

3.1.2 Breakdown of contributing LCA emissions sources

The effect of the interaction term was significant ($p < 0.001$) on the GWP associated with fossil fuel use, purchased feed and bedding, enteric methane, and N₂O emissions from management and application of animal manures. HFS had the lowest GWP per unit milk associated with fuel use and LFC the highest, while LFS and HFC were not significantly different. Individually, fossil fuel GWP was 6% higher in Low Forage regime and 6% higher in the Control line. In terms of the emissions embedded in purchased feed and bedding, HFS was again the most efficient, with GWP 24% lower than the least efficient LFC. Within a forage regime the Select line was 8% lower than Control with respect to purchased feed and bedding, and High Forage was 17% lower than Low Forage. Global warming potential associated with enteric fermentation was lowest in LFS and 32% higher in HFC. The individual effects upon GWP of the Low Forage regime and Select genetic line were 16% and 12% lower respectively in terms of enteric CH₄. LFS was the most efficient system in terms of N₂O emissions from deposition and management of manures. Conversely, HFC produced 63% more N₂O from animal manures compared with LFS. Emissions of N₂O from animal manures were 30% lower in High Forage regime than Low Forage, and 13% lower in the Select line.

3.1.3 Individual effects of forage regime and genetic line

The effect of production system was not significant upon the GWP associated with electricity use or methane from animal manures. Neither was the term significant for embedded emissions in production of manufactured fertilizers, N₂O emissions from applied manufactured fertilizers, or from crop residues. In these five emissions categories Low Forage feeding regime was more efficient than High Forage feeding regime (p<0.001). Amongst these categories, the individual effect of genetic line was only significant for N₂O emissions from crop residues, where emissions intensity was 5% lower in Select than Control. Of the total CH₄ produced, 88% was attributed to enteric fermentation, and this proportion was consistent across all systems. Off-farm emissions associated with purchased feed and bedding made the second highest contribution to GWP of the Low Forage regime (16%), one third greater than the contribution of N₂O from management and application of animal manures (12%). In the systems managed under High Forage regime, the embedded CO₂e emissions in feed and bedding contributed lower (11%) than those N₂O emissions associated with animal manures (14-15%). All emissions associated with manufactured fertilizer were higher in High Forage regime.

3.1.4 Land use

On-farm land use per kg ECM was greater for the HF groups (p<0.01), with HFC requiring the most farm land (0.98 m² kg⁻¹ ECM) and LFS the least (0.53 m² kg⁻¹ ECM). However, off-farm land was greater in LF groups, with LFC estimated to require the highest (0.93 m² kg⁻¹ ECM). Low Forage groups were estimated to require 57% more land off-farm than on-farm (p<0.01). Conversely, High Forage groups required 40% more land on-farm than off-farm. Total combined land use, incorporating land used for forages, grazing (where appropriate) and production of purchased feeds was greater in LF groups (p<0.01). LFC required the

highest total land use ($1.51 \text{ m}^2 \text{ kg}^{-1} \text{ ECM}$) to produce 1 kg ECM, followed by HFC, LFS and HFS (1.39 , 1.35 and $1.21 \text{ m}^2 \text{ kg}^{-1} \text{ ECM}$, respectively).

3.2. Contributions to uncertainty in estimated GWP

3.2.1 Uncertainty in GHG emissions sources

The regression coefficients determined for the defined component LCA categories contributing to the overall GWP are presented in Table 9. Nitrous oxide emissions associated with the deposition and management of animal manures was the source contributing the largest amount of variation in the overall GWP. Regression coefficients for uncertainty due to manure N_2O were considerably higher than those determined for the second highest contributor, the uncertainty due to variation in enteric CH_4 . These hotspots were consistent across all four dairy production systems. In both LFC and LFS, the CH_4 from animal manures was the third highest contributor of uncertainty, followed by N_2O associated with applied manufactured fertilizers, and then crop residues. Estimated N_2O emissions from manufactured fertilizers contributed the third largest amount of uncertainty to the total GWP of both HFC and HFS.

3.2.2 Key coefficients contributing to uncertainty

Six coefficients were identified as key parameters contributing the most to the observed uncertainty in overall GWP:

- i. IPCC coefficient for indirect emissions from volatilized nitrogen (EF_4)
- ii. IPCC coefficient for direct N_2O emissions (EF_1) from nitrogen input to soil

- iii. IPCC coefficient for emissions from animals' deposition at pasture ($EF_{3 \text{ PRP}}$) (for systems managed under High Forage regime only)
- iv. System-specific coefficient for excreted nitrogen rates
- v. System-specific coefficient for CH_4 from enteric fermentation
- vi. System-specific coefficient for CH_4 from manure management

Regression coefficients explaining the contribution of individual of emissions factors to the categories with the highest uncertainty are presented in table 10. In all four dairy production systems, the greatest contribution to uncertainty in N_2O emissions from deposition and management of animal manures arose from EF_4 , concerning indirect emissions from the volatilization of nitrogen. This coefficient was thus the dominant emissions factor in the category contributing the most uncertainty in the overall GWP, with system-specific excreted nitrogen coefficients making the second highest contribution. The IPCC coefficient for direct N_2O emissions (EF_1) was the dominant parameter in contributing to the uncertainty in GWP from applied fertilizers and manures, and also from crop residues. In two systems (HFC and HFS), the factor for N_2O emissions from excreta deposited on pasture by grazing animals ($EF_{3 \text{ PRP}}$) also contributed a large amount of the uncertainty within the N_2O from animal manures category. The influence of this emissions factor was not applicable to the two Low Forage systems.

4. Discussion

4.1. Effect of forage regime and genetic line on GWP

4.1.1 Emissions intensity of dairy production systems

The four dairy production systems in this study represent contrasting approaches to dairy herd management, and reflect a range of possible dairy systems. The results for the estimated GWP of the four Langhill systems are broadly in line with figures found in the literature for a conventional temperate European dairy production system (Thomassen et al., 2008; van der Werf et al., 2009). All four Langhill systems were estimated to have a lower GWP than the British average, estimated to be 1.31 kg CO₂e kg⁻¹ECM in the recent national study covering 415 dairy farms (DairyCo, 2012). This is likely due in part to the higher than average milk production of the Langhill herd, as well as a lower than average use of manufactured fertilizers. Farms in the national study will also have employed a range of different feeding regimes, diets, sources of feeds, and animal management into later lactations. Further, the DairyCo study calculations used national data sources, allocation techniques and emissions factors compliant with PAS:2050.

Basset-Mens (2008) noted that the strength of drawing direct comparisons between the results of different studies at dairy systems level has in the past been questionable. As the four systems were managed within the boundaries of the same farm, the results can confidently be directly compared to each other. These results suggest that there is potential to reduce the GWP per unit milk yield of a typical conventional dairy system by up to 24%. By improving the genetic merit alone, a dairy herd could potentially implement 9% reduction in emissions intensity. Genetic improvement is a relatively cost effective means by which to achieve reductions in GHG emissions, as the effect is cumulative and permanent (Bell et al., 2012b). Improvement of this nature necessarily proceeds gradually through breeding and would realistically take several years to return results. Once established, however, in the Langhill herd the higher genetic merit delivered an 18% increase in milk yield and contributed significantly to lowering overall emissions intensity. Similarly, results suggest that switching

to the Low Forage regime holds potential for a reduction in GWP of up to 16% per unit milk. These results in the present study agree with the findings of previous studies (Casey and Holden, 2005; Garnsworthy et al., 2012), who found that improving the milk yield of the herd would significantly reduce enteric CH₄ emissions and overall emissions per unit milk. Furthermore, the results of this study confirm that implementing the Low Forage regime reduced GWP per kg milk irrespective of cows' genetic merit.

4.1.2 Balance of enteric methane versus lost nitrogen

The key to reducing the overall GWP at system level lies in understanding where trade-offs arise in the dynamic nature of GHG production in dairy systems. Chagunda et al. (2009) showed that in dairy systems with low enteric CH₄ per unit milk had high excreted nitrogen and hence increased emissions from animal manures. Overall enteric CH₄ production was higher per cow in Low Forage regime, owing to the higher metabolizable energy (ME) content of the feed. Similarly, total enteric CH₄ was greater in the Select groups, attributed to higher DMI and thus higher MEI. However, high total enteric CH₄ was offset by the greater milk yield associated with Select genetic line and Low Forage diet. These results are consistent with the findings of Chagunda et al. (2009) and Bell et al. (2010). Further, the results from the current study showed that emissions from deposition and management of animal manures were lowest per unit milk for the highest yielding system. The HFC system produced 63% more N₂O per kg ECM from animal manures compared with LFS. The key to this difference lies in the different management practices under which animal manures were treated, and their different associated levels of emissions. Under the Low Forage regime, 100% of the fully housed lactating cows' excreta was stored under anaerobic conditions as liquid slurry. The default IPCC emissions factor for direct N₂O emissions from animal

manures (EF_3), when maintained in liquid storage without a crust as practiced at CRF, is zero (IPCC, 2006). In contrast, lactating High Forage cows spent an average of 148 (sd=15) days annually at pasture, where the emissions factor for deposition of animal manures (EF_{3PRP}) is 0.02 kg N_2O -N per kg nitrogen deposited (IPCC, 2006). This factor is also four times higher than 0.005 kg N_2O -N per kg stipulated for solid storage of farm manure. Thus under the High Forage regime, a lower rate of excreted lost nitrogen per cow resulted in higher emissions intensity from animal manures than under Low Forage.

4.1.3 Land use requirements and purchased feeds

Despite the differences in feed intake and ration composition among the dairy production systems, the overall on-farm forage crop requirements and hence the overall forage crop land requirements, were comparable. Although a large proportion of the High Forage TMR was from homegrown silages, the ration was only fed during periods when cows were not grazing. In contrast, in the Low Forage management regime, cows were provided with a low proportion of homegrown forages in the TMR throughout the year. However, when on-farm land use was expressed per kg ECM, the requirements were 0.59, 0.53, 0.98 and 0.88 m^2 kg^{-1} ECM for LFC, LFS, HFC and HFS, respectively. High Forage regime was estimated to require on average 0.37 m^2 more on-farm land per kg ECM than Low Forage regime. As forage crop land was comparable across systems, this difference was therefore almost exclusively due to grazing land needed for lactating cows in High Forage. Select line was also estimated to require 0.08 m^2 kg^{-1} ECM more than Control, due to a higher feed intake. On-farm land use by the dairy production system was a key difference in the higher manufactured fertilizer N_2O emissions estimated for High Forage regimes. Low forage groups. Further, on-farm land not required for pasture under Low Forage could be employed

by the in an environmental scheme for woodland sequestration or energy crops, contributing to further lower GWP of the dairy production system. Low Forage regime required more off-farm land, and more land overall compared to High Forage. Land use requirement under Low Forage was therefore inherently tied to the efficiency of crop production at national or even international level. This is particularly relevant to the global dairy industry in the case of South American production of soyabeans, where further off-farm emissions may also arise from the conversion of forest to productive agricultural land (Flysjo et al., 2012).

The emissions intensity associated with purchased feeds was 20% higher in Low Forage than in High Forage groups. Considering the high proportion of purchased feeds in the Low Forage ration, the difference between the two management regimes was lower than expected. This can partly be explained by the emissions intensity being offset by high milk yield in the Low Forage groups. However, the emissions factor for by-product grain was 0.030 kg CO₂e per kg of grain, compared with 0.375 and 0.360 kg CO₂e per kg of directly sourced wheat and barley respectively (Carbon Trust, 2010a). Thus the inclusion of by-products in the cows' ration led to lower embedded emissions than if all purchased feeds had been directly produced for animal consumption. The sourcing of by-product feeds was a key aspect of reducing emissions intensity in a Low Forage system. However, it is important to consider that if an increasing number of dairy systems switch to sourcing by-product feeds, demand may eventually exceed supply. The Low Forage regime is therefore more sensitive to any changes in the by-product market. Bell et al (2012a) noted that a growth in bio-ethanol production could lead to greater availability and competitive pricing of by-products for farmers. Security of supply will improve the future sustainability of the Low Forage regime which may even enable a higher inclusion of by-products in the diet, further reducing on- and off-farm feed production emissions. However, implementing a Low Forage ration comprising a different ratio or combination of purchased feed components could change the scale of

emissions intensities identified. Henriksson et al. (2011) noted that purchased animal feeds, for example barley, may differ in how and where it was cultivated, transported and processed in the feed industry. Thus when making comparisons between different studies, the GHG associated with the same purchased feed components may differ.

4.2. *Uncertainty in estimated GWP*

4.2.1 Key parameters contributing to uncertainty

Sources contributing the most uncertainty to results were N₂O emissions from management of manures, and enteric fermentation. This is broadly concurrent with Basset-Mens et al. (2009) and Flysjö et al, (2011) who found that, in similar analyses, the key parameter contributing the highest uncertainty was the emissions factor for direct N₂O emissions from excreta deposited directly on grazing (EF_{3PRP}), followed by CH₄ emissions from enteric fermentation. In a study of grazing systems in multiple locations, Lovett et al. (2008) found that the contribution to uncertainty from estimated N₂O was always greater than for CH₄. Both Basset-Mens et al. (2009) and Flysjö et al, (2011) employed a NZ specific emissions factor for deposition at pasture, 50% lower than the IPCC default value, however this factor still produced the highest uncertainty in their respective studies. Within the N₂O emissions from animal manures in the present study, however, the coefficient governing indirect emissions from volatilized nitrogen (EF₄) was the dominant factor. Under High Forage regime, EF_{3PRP} contributed the next greatest amount of variation to emissions from manures after EF₄ and the system specific nitrogen excretion rate. In the present study, average annual grazing under High Forage regime was 148 (sd=15) full days at grass over the period. The EF_{3PRP} parameter was not applicable to Low Forage regime as no animals were permitted to

graze pasture. Difference between the studies can be explained by the observation that Basset-Mens et al. (2009) based their analysis on an extensive grazing-based NZ dairy production system, with greater proportion of time at pasture but lower nitrogen excretion rate per cow and lower application of both stored manures and manufactured fertilizer.

4.2.2 Minimizing level of uncertainty

The overall range in estimated GWP was greater in High Forage systems, suggesting that Low Forage systems were less susceptible to influence of high uncertainty in emissions factors. This is supported by Gibbons et al. (2006), who stated that switching high yielding cows to a higher concentrate, less grass-based diet to reduce emissions was robust to uncertainty in GHG emissions. Although enteric fermentation contributed the most (44-47%) to the total GWP in all systems, this source did not contribute the most uncertainty overall. Enteric CH₄ had an emissions intensity three times greater than N₂O from animal manures under the High Forage regime, and four times greater under Low Forage regime, yet animal manure emissions made a larger contribution to the overall uncertainty. This goes to highlight that, for as much as a LCA method may seek to minimize the variation in its farm inventory data, a greater and unavoidable component of the uncertainty in LCA results will arise from employing standardized emissions factors. The IPCC coefficient for indirect emissions from volatilized nitrogen (EF₄) was the dominant factor in the emissions category contributing most to overall uncertainty. The coefficient for direct N₂O emissions from nitrogen applied to soil (EF₁) was also a dominant factor for all systems. In a study involving a comparable system (fully housed, Holstein Friesian cows, TMR with grass and maize silage and concentrates, farm gate LCA boundary), Zehetmeier et al. (2014) reported that nitrogen input to soil (EF₁) had the highest impact on uncertainty in GHG. The coefficient for deposition at

pasture (EF_{3PRP}) was a key contributor for High Forage systems. The uncertainty range for EF_4 stated in the literature amounts to a factor of 25, while uncertainties in EF_1 and EF_{3PRP} range by a factor of 10 and by around 8.5 respectively (IPCC, 2006). These standardized emissions factors necessarily contain a large uncertainty range as they aspire to be representative of the range of natural variability and physical conditions found on a national scale. In the present study, system-specific enteric CH_4 emissions factors by contrast were noted to have a coefficient of variation of around 7-10% across all systems. This would seem to illustrate a further advantage of employing the system-specific emissions factors in the present study or, more generally, employing Tier 3 values where possible in the LCA of dairy production systems. Conversely, it has been reported that statistical models which correlate nutrient intake with CH_4 production can vary widely where predictions are obtained for breeds, type of diet, nutrient intakes and environments outside those used in model construction (Mills et al., 2003; Boadi et al., 2004). However, the specific enteric CH_4 equation employed in the present study was previously determined to be most suitable for use in the Langhill herd, satisfying the range of production traits and diets, following a comparison of 22 equations in the literature (Bell et al., 2009). The IPCC note that variation introduced by any Tier 3 emissions factors employed is likely to be minimized, while uncertainties introduced by standardized emission factors are likely to dominate (IPCC, 2006). Lovett et al. (2008) also found that the coefficient of variation for enteric CH_4 was much lower than those for N_2O related emissions factors covering nitrogen leaching or applied fertilizers. Thus after many studies have gone to lengths to define and standardize the LCA methods, perhaps the most crucial aspect for confidence in LCA results in the future lies with narrowing the uncertainty parameters surrounding emissions factors, and developing countries' respective Tier 2 and Tier 3 coefficients. The present study suggests that increased definition of the inventory coefficients EF_1 and EF_4 would increase confidence in the

estimated GWP of all dairy production systems, while minimizing uncertainty in EF_3 would improve confidence in LCA results for those systems which involve grazing pasture.

5. Conclusions

This study found that the LFS system, where high genetic merit cows were managed under a Low Forage regime, had the lowest emissions intensity with respect to greenhouse gas emissions per unit of milk production. LFS was estimated to hold potential to reduce emissions intensity by 24% compared to average genetic merit cows managed under a High Forage regime. Individually, improving genetic merit of the herd and implementing Low Forage regime hold potential to reduce emissions intensity by 9% and 16% respectively. Key factors in the differences amongst systems were greater off-farm emissions under Low Forage regime, and greater on-farm nitrous oxide emissions associated with High Forage. In Low Forage groups, high overall emissions were matched with increased productivity, but this was not the case for the more extensive High Forage groups.

Three IPCC coefficients relating to nitrous oxide emissions (EF_1 , EF_4 , and $EF_{3\text{ PRP}}$), and system-specific emissions factors concerning cows' excreted nitrogen rate, enteric fermentation and manure methane, contributed the greatest uncertainty in results. The IPCC coefficients for direct atmospheric N_2O emissions (EF_1), indirect emissions from volatilized nitrogen (EF_4), and emissions from deposition at pasture ($EF_{3\text{ PRP}}$) should be prioritized for better definition in order to minimize uncertainty in future studies.

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Tables and figures

Table 1

Langhill dairy production systems described by system characteristics

Characteristic ^b	Units	Production System ^a							
		LFC		LFS		HFC		HFS	
		mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Milk yield	kg cow ⁻¹ day ⁻¹	29.2	4.45	34.8	4.95	22.9	3.55	26.4	4.46
Milk fat	g kg ⁻¹	36	7.0	38	7.4	39	6.5	41	7.1
Milk protein	g kg ⁻¹	31	3.6	33	3.9	32	3.9	33	4.4
Dietary CP	kg cow ⁻¹ day ⁻¹	3.22	0.32	3.62	0.37	2.94	0.34	3.22	0.38
Calving interval	days	388	53.3	407	72.3	396	57.7	407	72.5
Involuntary cull	%	18	4.5	31	7.7	10	5.0	16	6.2

^a LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select, and Select = representative of top 5% UK genetic merit for milk fat plus protein, Control = average genetic merit.

^b CP = crude protein

Table 2

Total Mixed Ration (TMR) components expressed as percentages (%) of the total formulation offered to lactating cows under Low Forage and High Forage regime and to dry cows

TMR Component	Low Forage %	High Forage %	Dry Cows %
Ryegrass silage	27.0	45.0	30.0
Wholecrop wheat alkalage	9.0	15.0	10.0
Wholecrop maize silage	9.0	15.0	10.0
Purchased concentrate/blend	53.9	24.2	4.1
Wheat straw	-	-	45.0
Minerals	1.1	0.8	0.9

Table 3
Mean and standard deviation (s.d.) of crop yields, land use and applied purchased nitrogen by
Langhill systems^a

		Grass silage		Maize silage		Wheat Alkalage		Pasture	
		mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Crop yield (dry matter)	t ha ⁻¹	10.3	1.5	11.9	2.1	11.6	2.3	10.3	1.5
Land Use	ha								
LFC		18.1	4.0	4.0	0.8	3.2	0.7		
LFS		18.0	4.2	4.2	0.7	3.4	0.9		
HFC		18.2	4.1	4.1	0.9	3.3	0.7	11.9	2.8
HFS		18.2	4.2	4.2	0.8	3.4	0.8	12.2	3.0
Purchased N applied	kg								
LFC		2740	393	47	26	224	84		
LFS		2716	276	51	26	230	75		
HFC		3083	777	48	24	239	102	876	464
HFS		2993	789	49	22	244	97	912	486

^a LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select

Table 4
Averages of annual Life Cycle input data by Langhill production system for livestock, energy use and animal production data

Input ^b		Units	Dairy Production System ^a							
			LFC		LFS		HFC		HFS	
			mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Livestock										
	Cows	n	47	4.1	43	5.6	50	5.9	48	5.6
	LW	kg cow ⁻¹	632	16.3	651	13.0	605	14.7	630	10.7
	DMI	kg cow ⁻¹ day ⁻¹	18.0	1.02	20.2	1.24	18.1	0.65	19.1	0.45
	MEI	MJ cow ⁻¹ day ⁻¹	210	12.0	236	15.0	184	9.5	201	7.7
	N intake	g cow ⁻¹ day ⁻¹	515	16.8	580	24.6	469	17.6	515	12.1
Energy use										
	Diesel	l	8347	2305	8387	2426	7230	2058	7162	2129
	Electricity	MWh	19.3	2.0	21.8	3.8	19.4	1.7	21.6	2.9
Animal production										
	MY	t	429	43.9	485	84.4	381	33.9	424	56.2
	F	t	15.3	1.61	18.5	3.53	14.6	1.00	17.1	2.06
	P	t	13.5	1.11	16.2	2.84	12.1	1.05	14.2	1.95
	DW	t	6.3	2.26	4.7	0.91	6.5	2.90	4.7	2.27

^a LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select, where Select = representative of top 5% UK genetic merit for milk fat plus protein, and Control = average genetic merit.

^b Cows = average no. cows in herd, LW = liveweight, DMI= dry matter intake, MEI = metabolizable energy intake, N = nitrogen, MY = total annual milk yield, F = milk fat, P = milk protein, DW = combined deadweight of sold livestock at 50% killout

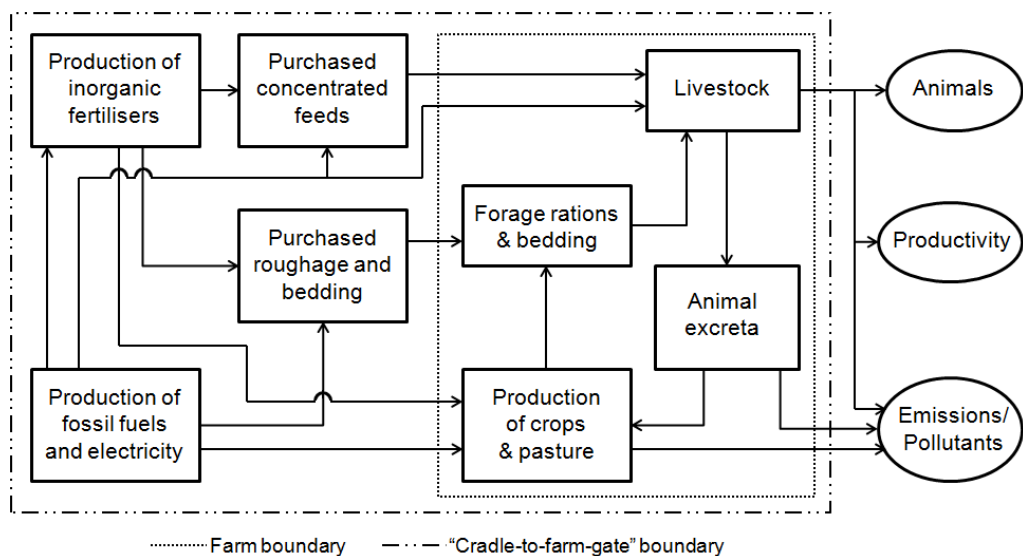


Figure. 1. Flow diagram showing farm and 'cradle-to-farm-gate' boundaries for product life cycle of Langhill dairy production systems

Table 5
Emissions factors with default values, uncertainty parameters and probabilistic distributions applied for sensitivity analysis

Factor	Description	Units	Default	Range	Distribution
EF ₁	^a Direct from applied fertilizer to soil	kgN ₂ O-N kgN ⁻¹	0.01	0.003-0.03	Beta
EF ₄	^a Volatilization, atmospheric deposition of nitrogen	kgN ₂ O-N kgN ⁻¹	0.01	0.002-0.05	Beta
EF ₅	^a Leaching and run-off	kgN ₂ O-N kgN ⁻¹	0.0075	0.0005-0.025	Beta
Frac _{LEACH}	^a % lost from leaching	%	30	10-80	Beta
EF _{3 PRP}	^a Direct from deposition of cows' excreta at pasture	kgN ₂ O-N kgN ⁻¹	0.02	0.007-0.06	Beta
Frac _{GASM}	^a Volatilization from animal excreta at pasture	%	20	5-50	Beta
Frac _{GASF}	^a Volatilization from applied fertilizers	%	10	3-30	Beta
EF _{3 SS}	^a Direct from solid storage of animal manure	kgN ₂ O-N kgN ⁻¹	0.005	0.0025-0.01	Beta
Frac _{SSV}	^a Volatilization from solid storage of animal manure	%	30	10-40	Beta
EF _{3 LS}	^a Direct from liquid storage of animal manure	kgN ₂ O-N kgN ⁻¹	0	0	-
Frac _{LSV}	^a Volatilization from liquid storage of animal manure	%	40	15-45	Beta
EF _{ICR}	^a Direct from crop residues	kgN ₂ O-N kgN ⁻¹	0.01	0.003-0.03	Beta
EF _{urea}	^a Direct emissions from applied urea	kgCO ₂ -C kgUrea ⁻¹	0.2	0.0-0.2	Triangular
EF _{Nex}	^b Excreted Nitrogen	kgN cow ⁻¹ year ⁻¹	Specific to system and age		Normal
EF _{ent}	^b Enteric methane	kgCH ₄ cow ⁻¹ year ⁻¹	Specific to system and age		Normal
EF _{man}	^b Manure methane	kgCH ₄ cow ⁻¹ year ⁻¹	Specific to system and age		Normal
EF _N	^c Production of nitrogen	kgCO ₂ e kgN ⁻¹	7.11	6.85-7.37	Beta
EF _P	^c Production of phosphate	kgCO ₂ e kgP ⁻¹	1.85	1.61-2.09	Beta
EF _K	^c Production of potash	kgCO ₂ e kgK ⁻¹	1.76	1.61-1.91	Beta
EF _{diesel}	^d Associated with red diesel	kgCO ₂ e l ⁻¹	3.176	2.818-3.533	Beta
EF _{petrol}	^d Associated with petrol	kgCO ₂ e l ⁻¹	2.667	2.368-3.065	Beta
EF _{elec}	^d Associated with electricity	kgCO ₂ e kWh ⁻¹	0.594	0.582-0.605	Normal

^aIPCC (2006)

^bSystem-specific calculations

^cCarbon Trust (2010b)/NEA (2011)

^dDEFRA (2011)

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2 **Table 6**

3 Breakdown of estimated land use and emissions embedded in purchased feed blends for High forage (HF) and Low forage (LF) rations

Purchased component	Whole crop		Proportion in blend		Land use per kg feed blend		Emissions per kg feed blend	
	Dry matter yield ^a	Embedded emissions ^b	LF	HF	LF	HF	LF	HF
	t ha ⁻¹	gCO ₂ e kg ⁻¹	%		m ² kg ⁻¹		gCO ₂ e kg ⁻¹	
Barley distillery grain	5.9	30		33.3		0.43		10.0
Wheat distillery grain	7.0	30	13	33.3	0.18	0.43	3.9	10.0
Wheat	7.0	354	34		0.46		118.0	
Sugar beet pulp	10.0	30	28		0.06		8.4	
Soyabean meal ^c	3.0	220	25		0.75		56.8	
Rapeseed meal	3.9	400		33.3		0.70		133.3
Complete blend					1.44	1.55	187.0	153.3

^a Average whole crop yields derived from: Craig & Logan (2012), Scottish Government (2012), DEFRA (2011b)

^b Carbon Trust (2010a)

^c Value for soya land use from Nielsen et al. (2003). Assumed sourced from Brazil, excludes land use change.

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1 **Table 7**

2 Breakdown of results from Analysis of Variance (ANOVA)^a, showing Global Warming Potential (GWP) per kilogram energy corrected milk (ECM),
 3 attributed to contributing categories of Life Cycle Assessment

Variable	Level ^b	Fossil fuels	Electricity	Manufactured fertilizer production	Purchased feed & bedding	Enteric fermentation	Animal manures	Animal manures	Manufactured fertilizer application	Crop residues	Total Overall GWP
		CO ₂	CO ₂	CO ₂ e	CO ₂ e	CH ₄	CH ₄	N ₂ O	N ₂ O	N ₂ O	CO ₂ e
Production system (F×G)	LFC	0.051 ^a	0.022	0.048	0.154 ^a	0.451 ^c	0.052	0.119 ^a	0.036	0.030	0.963 ^c
	LFS	0.048 ^b	0.024	0.045	0.143 ^b	0.393 ^d	0.049	0.103 ^b	0.034	0.028	0.866 ^d
	HFC	0.048 ^b	0.025	0.074	0.129 ^c	0.518 ^a	0.074	0.168 ^c	0.056	0.044	1.136 ^a
	HFS	0.046 ^c	0.026	0.071	0.118 ^d	0.462 ^b	0.073	0.148 ^d	0.053	0.042	1.040 ^b
	sem	0.0008	0.0008	0.0032	0.0030	0.0094	0.0027	0.0031	0.0024	0.0005	0.0163
Forage regime (F)	Low (LF)	0.049 ^a	0.023 ^b	0.046 ^b	0.149 ^a	0.422 ^b	0.051 ^b	0.111 ^a	0.035 ^a	0.029 ^b	0.914 ^b
	High (HF)	0.047 ^b	0.026 ^a	0.073 ^a	0.124 ^b	0.490 ^a	0.073 ^a	0.158 ^b	0.055 ^b	0.043 ^a	1.088 ^a
	sem	0.0006	0.0005	0.0027	0.0020	0.0067	0.0019	0.0020	0.0017	0.0004	0.0116
Genetic line (G)	Control (C)	0.049 ^a	0.024	0.061	0.142 ^a	0.484 ^a	0.063	0.144 ^a	0.046	0.037 ^a	1.049 ^a
	Select (S)	0.047 ^b	0.025	0.058	0.131 ^b	0.428 ^b	0.061	0.125 ^b	0.043	0.035 ^b	0.953 ^b
	sem	0.0006	0.0005	0.0027	0.0020	0.0067	0.0019	0.0021	0.0017	0.0004	0.0116
R ² value		0.94	0.95	0.89	0.87	0.85	0.88	0.94	0.89	0.97	0.91

4 ^a All results presented as least squares means (ls_m) with standard errors of the mean (sem), and expressed in terms of kilograms of carbon dioxide equivalents per kilogram
 5 Energy Corrected Milk (kg CO₂e kg ECM⁻¹). Different superscripts within a column denote significant differences between levels of same variables (p<0.001).

6 ^b LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select

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Table 8

Results from Analysis of Variance (ANOVA)^a showing land use per kilogram of Energy Corrected Milk (ECM)

Variable	Level ^b	Land Use ^a		
		On-farm m ² kgECM ⁻¹	Off-farm m ² kgECM ⁻¹	Total land m ² kgECM ⁻¹
Production system (FxG)	LFC	0.59 ^b	0.93 ^a	1.51 ^a
	LFS	0.53 ^b	0.82 ^a	1.35 ^b
	HFC	0.98 ^a	0.41 ^b	1.39 ^b
	HFS	0.88 ^a	0.33 ^b	1.21 ^c
	sem	0.037	0.047	0.073
Forage regime (F)	Low (LF)	0.56 ^b	0.88 ^a	1.43 ^a
	High (HF)	0.93 ^a	0.37 ^b	1.30 ^b
	sem	0.037	0.037	0.017
Genetic line (G)	Control (C)	0.78 ^a	0.67 ^a	1.45 ^a
	Select (S)	0.70 ^b	0.58 ^b	1.28 ^b
	sem	0.012	0.014	0.013
R ² value		0.93	0.95	0.78

^a All results presented as least squares means (lsm) with standard errors of the mean (sem). Different superscripts within a column denote significant differences between levels of same variables (p<0.01).

^b LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select

Table 9

Regression coefficients explaining contribution of variation in each emissions source to uncertainty in estimated overall global warming potential (GWP), with respective ranges in uncertainty^a

Contributing category variable	Production System ^b											
	LFC			LFS			HFC			HFS		
	Rank	Coeff	Range	Rank	Coeff	Range	Rank	Coeff	Range	Rank	Coeff	Range
N ₂ O animal manures	1	0.76	0.39	1	0.74	0.28	1	0.73	0.47	1	0.73	0.44
CH ₄ enteric fermentation	2	0.44	0.23	2	0.44	0.20	2	0.44	0.27	2	0.43	0.25
CH ₄ animal manures	3	0.32	0.17	3	0.35	0.14	5	0.28	0.17	4	0.31	0.18
N ₂ O purchased fertilizer application	4	0.27	0.11	4	0.28	0.09	3	0.34	0.16	3	0.35	0.17
N ₂ O crop residues	5	0.24	0.09	5	0.25	0.08	4	0.29	0.14	5	0.29	0.13
CO ₂ e fossil fuels	6	0.05	0.02	6	0.05	0.01	6	0.04	0.01	6	0.04	0.01
CO ₂ e purchased fertilizer production	7	0.01	0.01	7	0.01	0.01	7	0.02	0.01	7	0.01	0.01
CO ₂ e electricity	8	0.01	0.01	8	0.01	0.01	8	0.01	0.01	8	0.01	0.01
Overall GWP			0.50			0.41			0.61			0.67

^a Range in overall GWP expressed in kilograms of carbon dioxide equivalents per kilogram energy corrected milk

^b LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select

Table 10

Regression coefficients explaining contribution of variation in emissions factors to uncertainty in estimated nitrous oxide emissions from animal manures, applied purchased fertilizers and crop residues

Emissions factor ^a	Source of estimated emissions											
	Animal manures				Applied purchased fertilizers				Crop residues			
	LFC	LFS	HFC	HFS	LFC	LFS	HFC	HFS	LFC	LFS	HFC	HFS
EF ₁					0.92	0.91	0.91	0.91	0.92	0.92	0.92	0.92
EF _{3 PRP}			0.37	0.41								
EF ₄	0.88	0.87	0.75	0.73	0.19	0.19	0.19	0.19				
EF ₅	0.18	0.17	0.18	0.18	0.26	0.26	0.26	0.26	0.30	0.30	0.30	0.30
EF _{N ex}	0.29	0.33	0.41	0.44								
EF _{SS}	0.15	0.13	0.14	0.12								
Frac _{GASF}					0.11	0.11	0.11	0.11				
Frac _{GASM}	0.13	0.13	0.14	0.15								
Frac _{LEACH}	0.12	0.11	0.12	0.12	0.20	0.20	0.20	0.19	0.23	0.22	0.22	0.22
Frac _{LSV}	0.05	0.06	0.03	0.03								
Frac _{SSV}	0.01	0.01	0.01	0.01								
R ² value	0.97	0.97	0.97	0.97	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

^a EF₁ = direct emissions from nitrogen input to soil, EF_{3 PRP} = direct from deposition of cows' excreta at pasture, EF₄ = indirect emissions from volatilised N, EF₅ = emissions from leaching and runoff, EF_{N ex} = System specific nitrogen excretion rate, EF_{SS} = direct from solid storage, Frac_{GASF} = % volatilisation from fertiliser, Frac_{GASM} = % volatilisation from manures, Frac_{LEACH} = % leaching, Frac_{LSV} = % volatilisation from liquid storage, Frac_{SSV} = % volatilisation from solid storage. Where: LFC = Low Forage Control, LFS = Low Forage Select, HFC = High Forage Control, LFS = High Forage Select